

1 Are operational plantations meeting expectations? A large-scale assessment of realized vs
2 anticipated yield in eastern Canada

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23 **Abstract**

24 Forest plantations play an increasingly important role in meeting global demand for
25 wood. They usually have higher yield than naturally regenerated forests. Thus,
26 plantations can support economically viable wood production, enable forest conservation
27 elsewhere, help mitigate climate change by contributing to carbon sequestration and
28 increase forest resilience and resistance to biotic and abiotic stressors. If yield of
29 plantations is not as high as anticipated, then their use could generate important
30 sustainability issues. There are still major gaps in our understanding of the factors that
31 influence yield, even with respect to black spruce, white spruce, and jack pine, three of
32 the most commonly planted tree species in northeastern North America. Our objective
33 was to evaluate the yield of forest plantations of these species over a 416 000 km² region
34 that was representative of northeastern North American forests. Contrary to our
35 prediction, realized yield of operational plantations was consistently lower than
36 anticipated. Site index and competition both played a significant role in determining the
37 yield of plantations. In the context of uncertain realized yield of operational plantations,
38 we emphasize the necessity of relying on adaptive management to determine harvest
39 levels that are compatible with sustainable management objectives.

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41 **Keywords:** sustainable forest management, allowable cut, silviculture, boreal forest,
42 temperate forest

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Introduction

Forest plantations play an increasingly important role in meeting global demand for wood products (McEwan et al. 2019) and are established to meet economic, conservation and climate change issues (Thiffault et al. 2023). They usually have higher yield than naturally regenerated forests, given that they make better use of the space due to optimized stocking that maximize space use, and applications of cultural treatments such as vegetation management and are based upon genetically improved material (e.g., Ackzell 1993; Paquette and Messier 2010). Thus, plantations can support economically viable wood production (Gardiner and Moore 2014), while enabling forest conservation elsewhere (Betts et al. 2021; Royer-Tardif et al. 2021). Plantations can also help mitigate climate change by contributing to carbon sequestration (Wade et al. 2019; Ménard et al. 2022; Portmann et al. 2022), and by increasing forest resilience and resistance to biotic and abiotic stressors (Ray et al. 2015; Palik et al. 2022). Hence, issues related to sustainability, such as ensuring economically viable wood production, supporting forest conservation, and promoting carbon sequestration, may arise if the yield of plantations does not meet anticipated levels.

In forest management plans, forest yield is typically estimated using a combination of field measurements, remote sensing data, and growth and yield models. Yield models for plantations are usually developed for specific tree species, site fertility and management regimes (e.g., Stiel and Berry 1967; Bolghari and Bertrand 1984). They are based upon data that are collected from long-term research plots or from networks of permanent sampling plots, taking into account factors such as tree growth rates, mortality rates, and competition among trees. Yet, yield in forest plantations is driven by a complex array of

67 factors, including species selection, site preparation, planting density, and management
68 practices. For example, Fu et al. (2007) demonstrated a significant increase in the growth
69 of planted jack pine (*Pinus banksiana* Lamb.), black spruce (*Picea mariana* [Mill.]
70 B.S.P.), white pine (*Pinus strobus* L.), and white spruce (*Picea glauca* [Moench] Voss)
71 over a 15-year period. This growth was observed to be significantly higher following
72 high mechanical site preparation intensity, without additional vegetation management
73 treatments. However, when chemical vegetation management was applied, site
74 preparation showed no discernible impact on tree growth. Thus, the yield of plantations
75 that are incorporated into forest management plans is highly dependent upon the data that
76 are used for constructing growth and yield models. This dependence stresses the
77 importance of establishing and managing plantations according to the same standards that
78 are used to generate growth and yield models, to ensure that anticipated production is
79 realized. Failure to do so would compromise the attainment of sustainable forest
80 management objectives.

81 Moreover, regional differences in climate, soil and other environmental factors can
82 substantially affect the yield of forest plantations, stressing the need for region-specific
83 predictors of growth. For example, recent research that has simulated the effects of
84 various CO₂ emission scenarios has suggested that stand-level yield under a changing
85 climate will vary by species, site quality, geographic locale, and emission scenario
86 (Newton 2016). Yet, significant gaps remain in our understanding of the factors that
87 influence yield, even with respect to black spruce, white spruce, and jack pine, three of
88 the most frequently planted tree species in northeastern North America (CCFM 2023).

In this context, our objective was to evaluate the yield of forest plantations, which were established in Quebec, Canada, over a 416 000 km² region that is representative of northeastern North American forests. More specifically, we aimed to identify the drivers of forest plantation yield. We predicted that plantation yield would be as high as anticipated, given that silviculture scenarios usually comprise adequate vegetation management strategies (MRN 2013). We also predicted that site index, planting density and competition would be important drivers of plantation yield (Wiensczyk et al. 2011; Neufeld et al. 2014; Barrette et al. 2019, 2021; Sharma 2022). To verify our predictions, we studied yield in operational plantations of the three most commonly planted tree species in northeastern North America.

Materials and methods

Study area

Our study area encompasses the actively managed forest region of Quebec (eastern Canada), which includes temperate and boreal forests that have been classified into four ecological regions (Grondin et al. 2007; Fig. 1). Climatic conditions in southern ecological regions are warmer than in northern regions, as would be expected, while precipitation regimes are generally similar (Table 1).

The main natural disturbances include insect outbreaks (e.g., eastern spruce budworm [*Choristoneura fumiferana*]), windthrows and wildfires (Barrette et al. 2020). The most abundant tree species are black spruce, balsam fir (*Abies balsamea* [L.] Mill.), white or paper birch (*Betula papyrifera* Marsh.), yellow birch (*B. alleghaniensis* Britt.) and sugar maple (*Acer saccharum* Marsh.). Depending on the ecological region, these species are found in mixtures with varying densities of companion species, such as white spruce, red

112 spruce (*Picea rubens* Sarg.), jack pine, eastern white pine, red pine (*Pinus resinosa* Sol.
 113 ex Aiton), eastern hemlock (*Tsuga canadensis* [L.] Carrière), eastern white cedar or
 114 arborvitae (*Thuja occidentalis* L.), eastern larch or tamarack (*Larix laricina* [Du Roi] K.
 115 Koch), balsam poplar (*Populus balsamifera* L.), bigtooth aspen (*Populus grandidentata*
 116 Michx.), trembling aspen (*Populus tremuloides* Michx.), red maple (*Acer rubrum* L.),
 117 American beech (*Fagus grandifolia* Ehrh.), red oak (*Quercus rubra* L.), silver maple
 118 (*Acer saccharinum* L.), American ash (*Fraxinus americana* L.), American basswood
 119 (*Tilia americana* L.), and American elm (*Ulmus americana* L.) (MRN 2013).

120 Data

121 We used a network of 475 sample plots that were established by the Government of
 122 Quebec to monitor operational plantation yield of the three most commonly planted tree
 123 species in northeastern North America, i.e., black spruce, white spruce and jack pine (Fig.
 124 1). These plots were established from 1995 to 1999 in plantations that were about 8-
 125 years-old at the time. Planted trees were then tagged for monitoring purposes. Trees with
 126 DBH (diameter at breast height, 1.3 m) ≥ 1.1 cm were counted within 400-m² circular
 127 plots, by species, origin (i.e., planted or naturally regenerated). DBH of each tree was
 128 measured in millimeters. Height (cm) of the 4 highest planted trees of the stand was also
 129 measured for dominant height estimation. Measurements were repeated up to six times in
 130 each plot, on a 5-year cycle. Vegetation management was performed based on
 131 governmental guidelines which includes site preparation and a number of tendings
 132 dependent on competition levels (MRN 2013; Barrette et al. 2020b).
 133 Potential natural vegetation in each plot was obtained from the Eco-Forest Stand Map
 134 (MRNF 2009). Potential natural vegetation is a stand-level land classification unit that is

determined by climate, superficial deposits, soil texture, slope, drainage and indicator plant species in the understory (Grondin et al. 2014). By considering potential natural vegetation, we can anticipate the composition and resilience-driven successional trajectories of a given site (Barrette et al. 2019, 2021). Resilience refers to the capacity of a system to absorb a disturbance and reorganize so that the same structure and functions are essentially recovered (Gunderson, 2000). Assessing potential natural vegetation can assist in determining whether the plantation scenario aligns with or deviates from the resilience-driven successional trajectories. For example, a black spruce plantation scenario carried out on a black spruce potential natural vegetation or a black spruce plantation scenario carried out on a balsam fir potential natural vegetation, respectively. This assignment helps predict whether planted trees would be prone to intraspecific or interspecific competition (Barrette et al. 2019, 2021). Thus, the four ecological regions of our study can support a diversity of potential natural vegetation types, but they will typically maintain the potential natural vegetation of the species that denotes the region, e.g., black spruce-moss region will typically hold black spruce potential natural vegetation (Grondin et al. 2007). It should be noted that a white spruce plantation scenario will always deviate from resilience-driven successional trajectories, given that white spruce potential natural vegetation does not occur within the four ecological regions (Grondin et al. 2007; Barrette et al. 2014; Grondin et al. 2014).

Data analysis

To evaluate the yield of operational plantations, we compared their realized with their anticipated yield. To obtain realized plantation yield, we calculated stand basal area based on DBH of planted trees for each plot, by time-since-planting, i.e., classes of 10-15, 16-

158 20, 21-25 and 26-34 years. These age classes were used to balance the number of
159 plantations in each class, while representing age classes that are relevant to silviculture.
160 To obtain anticipated yield of planted trees, we used stand basal area growth models that
161 were developed for black spruce and jack pine plantations (Auger et al. 2021) and for
162 white spruce plantations (Prégent et al. 2010; Auger and Power 2021). Anticipated yield
163 of planted trees for each plantation at each measurement was estimated with the growth
164 model according to their age, planting density and site index (i.e., mean height of the 100
165 highest trees per hectare in meters at age 25-years-old, estimated using equations from
166 Auger et al. 2021 and Prégent et al. 2010). To evaluate competition, we calculated stand
167 basal area based on the DBH of naturally regenerated trees for each plot, by species and
168 time-since-planting. Competition was quantified as a percentage of the total stand basal
169 area, calculated as: $(\text{basal area of naturally regenerated trees} / (\text{basal area of naturally}$
170 $\text{regenerated trees} + \text{basal area of planted trees})) \times 100$. Planted trees were excluded from
171 the assessment of potential competitors, as our focus was on their yield. Composition of
172 the competition was analyzed specifically in plantations with a scenario that deviates
173 from or is aligned with resilience-driven successional trajectories. We used potential
174 natural vegetation to determine whether the plantation scenario aligns with or deviates
175 from resilience-driven successional trajectories (Barrette et al. 2019, 2021).
176 The difference between realized plantation yield and anticipated yield of planted trees
177 (i.e., yield gap) was calculated for each plantation for the oldest age class (i.e., 26- to 34-
178 years-old) since it provides an extended time depth for comprehensive analysis. The yield
179 gap of a given plantation was expressed as a percentage of anticipated yield for that
180 plantation: $(\text{realized yield} - \text{anticipated yield}) / \text{anticipated yield} \times 100$. Plantations with a

realized yield lower than anticipated by more than 5% were considered to be unsuccessful; otherwise, they were considered successful. We analyzed the linear relationship between the yield gap and potential yield drivers (i.e., site index, planting density or competition; Wiensczyk et al. 2011; Neufeld et al. 2014; Barrette et al. 2019, 2021; Sharma 2022) with simple linear regressions by ecoregion and species (PROC MIXED, SAS/STAT 15.1; SAS Institute, Cary, NC). We also analyzed differences between successful and unsuccessful plantations for each potential yield driver with analysis of variance (one-way ANOVA), using yield status (i.e., successful or unsuccessful) as a fixed effect. We used $\alpha = 0.05$ as the significance threshold. Analyses conformed to normality and homogeneity of variance requirements.

Results

Realized plantation yield

Realized yield was always lower than anticipated yield 26 to 34 years after planting (Fig. 2). Site index was a significant yield driver in boreal regions, more so than in the temperate regions. The yield gap generally decreased with increasing site index in all ecological regions (Fig. 3). In boreal regions, site index of successful plantations was always higher than the site index of unsuccessful plantations, while site index was generally similar between successful and unsuccessful plantations in temperate regions (Tables 2 and 3).

Planting density was rarely a significant yield driver. The yield gap was almost always not related to planting density (Fig. 4). Moreover, planting density was generally similar between successful and unsuccessful plantations (Tables 2 and 3).

203 Competition was a significant yield driver in both boreal and temperate regions. The
204 yield gap generally decreased with increasing competition (Fig. 5). Moreover,
205 competition was always higher in successful plantations than in unsuccessful plantations
206 (Tables 2 and 3).

207 *Composition of the competition in unsuccessful plantations*

208 In unsuccessful black spruce plantations, balsam fir and hardwoods were the main
209 naturally regenerated species when the plantation scenario deviated from resilience-
210 driven successional trajectories, i.e., black spruce plantations that were located on balsam
211 fir potential natural vegetations (Fig. 6). Other conifers and black spruce also regenerated
212 naturally but mainly in boreal regions. When the plantation scenario was aligned with
213 resilience-driven successional trajectories (i.e., black spruce plantations located on black
214 spruce potential natural vegetations), black spruce was the main naturally regenerated
215 species followed mostly by other coniferous and hardwoods in the black spruce moss
216 region, by other conifers in balsam fir-white birch region, and by balsam fir and
217 hardwoods in the balsam fir-yellow birch region (Fig. 7).

218 In unsuccessful white spruce plantations, for which the scenario always deviates from
219 resilience-driven successional trajectories, balsam fir and hardwoods were the main
220 naturally regenerated species (Fig. 6). Black spruce and other conifers also regenerated
221 naturally but mainly in boreal regions.

222 In unsuccessful jack pine plantations, balsam fir and hardwoods were the main naturally
223 regenerated species when the plantation scenario deviated from resilience-driven
224 successional trajectories, i.e., jack pine plantations that were located on balsam fir
225 potential natural vegetation types (Fig. 6). Jack pine also regenerated naturally but only in

boreal regions. When the plantation scenario was aligned with resilience-driven successional trajectories (i.e., jack pine plantations located on black spruce potential natural vegetations), black spruce was the main naturally regenerated tree species, followed mostly by jack pine and other coniferous in the black spruce moss region, by jack pine in the balsam fir-white birch region, and by hardwoods in the balsam fir-yellow birch region (Fig. 7).

Discussion

Contrary to our prediction, realized yield of operational plantations was consistently lower than anticipated yield that had been projected by growth and yield models for plantations of similar ages, planting densities and site indices. The yield gap at ages 26-34 varied between -97% and +83%, depending on ecological region and planted species. This finding suggests that anticipated yield may not be achieved in operational plantations, thereby potentially compromising the attainment of sustainable forest management objectives. For instance, in Quebec, where about 20% of annual harvested sites are regenerated using plantation scenarios (Lapointe 2022), the calculation of allowable cut levels considers the potential increase in yield of planted areas compared to natural regeneration (Poulin 2013). To account for differences between anticipated and realized yield, an adaptive management process is necessary. Adaptive management is a process involving periodic monitoring to assess the achievement of objectives and the need for adaptations in response to new contexts or knowledge (Barrette et al 2014). As such, the calculation of allowable cut levels in Quebec is revised every five years, taking into account the most recent survey data and research findings. This practice is crucial in

the context of sustainable forest management, where the success of plantation forestry plays a pivotal role in determining the level of sustainable harvest (BFeC 2015). As predicted, site index played a significant role in determining the yield status of plantations in boreal regions, but it did not have much influence on yield status in temperate regions. In boreal regions, we observed that yield of plantations that were established on sites with low site indices was lower than anticipated, while those that were established on sites with higher indices exhibited the anticipated yield. One possible explanation for the yield gap in sites with lower site index could be their underrepresentation in the plot network that was used for constructing growth models. Prigent and Végiard (2000) studied the growth and yield of 41 of the oldest black spruce plantations in northern Quebec on mesic sites (~98%) and found that nearly 34% of the plots that were studied had site quality indices below the minimum value used to construct yield tables for this species at that time (Prigent et al. 1996). Although the latest growth models have incorporated a greater number of plantations, there continues to be an underrepresentation of lower site index classes, notably for black spruce and white spruce plantations (Prigent et al. 2010; Auger et al. 2021). Another factor could be variation in plantation establishment techniques. After harvest, low fertility sites in boreal ecosystems of northeastern Canada are typically colonized by ericaceous shrubs, which negatively affect conifer establishment and growth (Mallik 2003). Studies have demonstrated that mechanical site preparation treatments can enhance seedling growth, particularly by reducing understory vegetation cover and rhizomatous growth (Wotherspoon et al. 2020; Reicis et al. 2023). Yet, the intensity of the treatment can influence its effect on seedling growth, with more intensive treatments

favouring faster height growth compared to lower intensity treatments (Thiffault et al. 2004), thereby affecting the site index over time. Consequently, differences between establishment practices in the modelling plots and operational plantations may lead to variation in yield.

Contrary to our prediction, planting density was rarely a driver of yield. Planting density is usually recognized to play an important role in plantation yield (Thiffault et al. 2021). Yet, we may have not been able to link plantation density to the yield status of plantations, given that it did not vary significantly in our plots. Moreover, yield tables for black spruce, white spruce and jack pine are more strongly affected by site index than by planting density (Prégent et al. 2010, Auger et al. 2021).

As predicted, competition was a significant driver of yield in both boreal and temperate regions where it played a major role in determining the yield status of plantations. Paquette and Messier (2011) also found that tree yield was determined mostly by the intensity of competition in such regions. Moreover, it is widely recognized that yield of forest plantations is closely linked to competition by naturally regenerating tree species (Wiensczyk et al. 2011; Hawkins et al. 2012; Faure-Lacroix et al. 2013; Neufeld et al. 2014; Bérubé-Deschênes et al. 2017). Finally, Anyomi et al. (2014) also found that species composition and successional changes drive yield more so than do climatic effects and site index.

Despite vegetation management was performed (MRN 2013; Barrette et al. 2020b), competition from naturally regenerated trees likely occurred in forest plantations because of resilience-driven, successional trajectories. Depending on whether the plantation scenario was aligned with or deviated from resilience-driven successional trajectories,

294 planted species respectively suffered mostly from intraspecific or interspecific
295 competition. It is recognized that naturally regenerating tree species can recover to the
296 detriment of planted species because of the resilience of the natural forest (Barrette et al.
297 2019, 2021).

298 **Forest management implications**

299 Forest plantations could generate important sustainability issues if their yield is not as
300 high as anticipated (Gardiner and Moore 2014; Wade et al. 2019; Betts et al. 2021;
301 Portmann et al. 2022). To ensure that plantations promote sustainability, forest managers
302 could favour establishment of plantations in stands with high site indices, but more
303 importantly, favour plantation scenarios that are aligned with resilience-driven,
304 successional trajectories that would reduce interspecific competition (Barrette et al. 2019,
305 2021).

306 Efforts have already been made to map site index values for white spruce, black spruce
307 and jack pine plantations in eastern Canada (Barrette et al. 2022). Yet these maps do not
308 consider the potential effects of competition that are incurred by naturally regenerated
309 trees. Integrating plantation scenarios that are aligned with resilience-driven successional
310 trajectories to these existing site index maps could help to identify the best sites for
311 establishing forest plantations. Moreover, integration of this information could help
312 determine the level of tending that is needed to reach anticipated plantation yield. A
313 within-hectare specific predictors of growth would also eventually be useful to ensure
314 plantation reach anticipated yield (Watt et al. 2017).

315 Reducing interspecific competition in white spruce plantations may prove more difficult,
316 since there is no resilience-driven successional trajectory that is oriented towards white

spruce stands (Grondin et al. 2007; Grondin et al. 2014; Barrette et al. 2014). White spruce plantations, therefore, may need more intensive tending for them to achieve anticipated yield even with the use of site index maps. Finally, in the context of uncertain realized yield of operational plantations, we emphasize the necessity of relying on adaptive management to determine harvest levels that are compatible with sustainable management objectives.

Acknowledgements

This work was supported by Project 142332110, Direction de la recherche forestière of the Ministère des Ressources Naturelles et des Forêts, de la Faune et des Parcs du Québec (MRNFQ). This work aligns with the objectives of the IUFRO Task Force on Resilient Planted Forests Serving Society and Bioeconomy, of which Nelson Thiffault is a member. We thank Jean Noël for help in figure preparation and W.F.J. Parsons for English language revision. There are no competing interests for all authors. Data are located at and can be accessed following a consent from the government of Québec.

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502

503 Table 1. Climatic conditions in the four ecological regions.

	Mean annual temperature (°C)	Mean annual precipitation (mm)	Mean annual number of frost-free days
<i>Boreal regions</i>			
Black spruce-moss region	-2.0	1000	165
Balsam fir-white birch region	0.5	1200	175
<i>Temperate regions</i>			
Balsam fir-yellow birch region	1.5	1100	180
Sugar maple-yellow birch region	3.0	1100	190

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Table 2. Characteristics of successful (Succ.) and unsuccessful (UnSucc.) plantations by ecological region and planted species. Different superscript letters indicate significant differences (see Table 3) .

	Number of plots		Site index (m)		Planting density (trees·ha ⁻¹)		Competition (%) *	
	Succ.	UnSucc.	Succ.	UnSucc.	Succ.	UnSucc.	Succ.	UnSucc.
<i>Boreal regions</i>								
Black spruce-moss region								
Black spruce plantation	11	53	8 ^a	7 ^b	2458 ^a	2424 ^a	7 ^a	50 ^b
Jack pine plantation	10	33	11 ^a	9 ^b	2587 ^a	2308 ^b	4 ^a	27 ^b
Balsam fir-white birch region								
Black spruce plantation	28	54	9 ^a	8 ^b	2565 ^a	2339 ^b	13 ^a	44 ^b
White spruce plantation	10	52	11 ^a	9 ^b	2602 ^a	2443 ^a	4 ^a	33 ^b
Jack pine plantation	9	44	12 ^a	10 ^b	2327 ^a	2300 ^a	4 ^a	22 ^b
<i>Temperate regions</i>								
Balsam fir-yellow birch region								
Black spruce plantation	16	42	10 ^a	10 ^a	2570 ^a	2576 ^a	10 ^a	26 ^b
White spruce plantation	15	28	11 ^a	11 ^a	2334 ^a	2618 ^a	6 ^a	26 ^b
Jack pine plantation	3	17	14 ^a	13 ^a	2359 ^a	2682 ^a	5 ^a	7 ^a
Sugar maple-yellow birch region								
Black spruce plantation	13	11	10 ^a	11 ^a	2808 ^a	2716 ^a	8 ^a	10 ^a
White spruce plantation	10	16	12 ^a	11 ^b	2657 ^a	2638 ^a	6 ^a	19 ^b

* 26–34-year-old plantations

Table 3. ANOVA and associated p -values of characteristics of plantations by ecological region and planted species. Numerator degrees-of-freedom is 1 for all analyses, with one fixed effect (yield status, i.e., successful or unsuccessful). Df den. is denominator degrees-of-freedom. Significant effects ($p < 0.05$) are highlighted in boldface.

	Df den.	Site index		Planting density		Competition (%) *	
		F -value	p -value	F -value	p -value	F -value	p -value
<i>Boreal regions</i>							
Black spruce-moss region							
Black spruce plantation	79	6.91	0.010	0.12	0.734	39.23	< 0.001
Jack pine plantation	51	16.04	< 0.001	4.60	0.037	12.14	0.001
Balsam fir-white birch region							
Black spruce plantation	104	5.05	0.027	9.78	0.002	63.34	< 0.001
White spruce plantation	79	20.49	< 0.001	2.29	0.134	18.28	< 0.001
Jack pine plantation	68	5.81	0.019	0.05	0.830	15.15	< 0.001
<i>Temperate regions</i>							
Balsam fir-yellow birch region							
Black spruce plantation	68	2.14	0.148	0.00	0.957	9.03	0.004
White spruce plantation	46	1.49	0.228	4.03	0.051	14.92	< 0.001
Jack pine plantation	28	3.22	0.084	2.72	0.110	0.71	0.406
Sugar maple-yellow birch region							
Black spruce plantation	28	1.35	0.256	0.15	0.706	0.32	0.578
White spruce plantation	29	4.48	0.043	0.02	0.884	10.99	0.003

* 26–34-year-old plantations

Figure captions

Fig 1 Locations of plots in plantations of black spruce (black triangles; $n = 228$), white spruce (white triangles; $n = 131$) and jack pine (white circles; $n = 116$). Figure 1 was created using ArcMap version 10.4.1 and assembled from the open access data of the MRNF available at <https://mffp.gouv.qc.ca/le-ministere/acces-aux-donnees-gratuites/>.

Fig 2 Realized vs anticipated plantation yield.

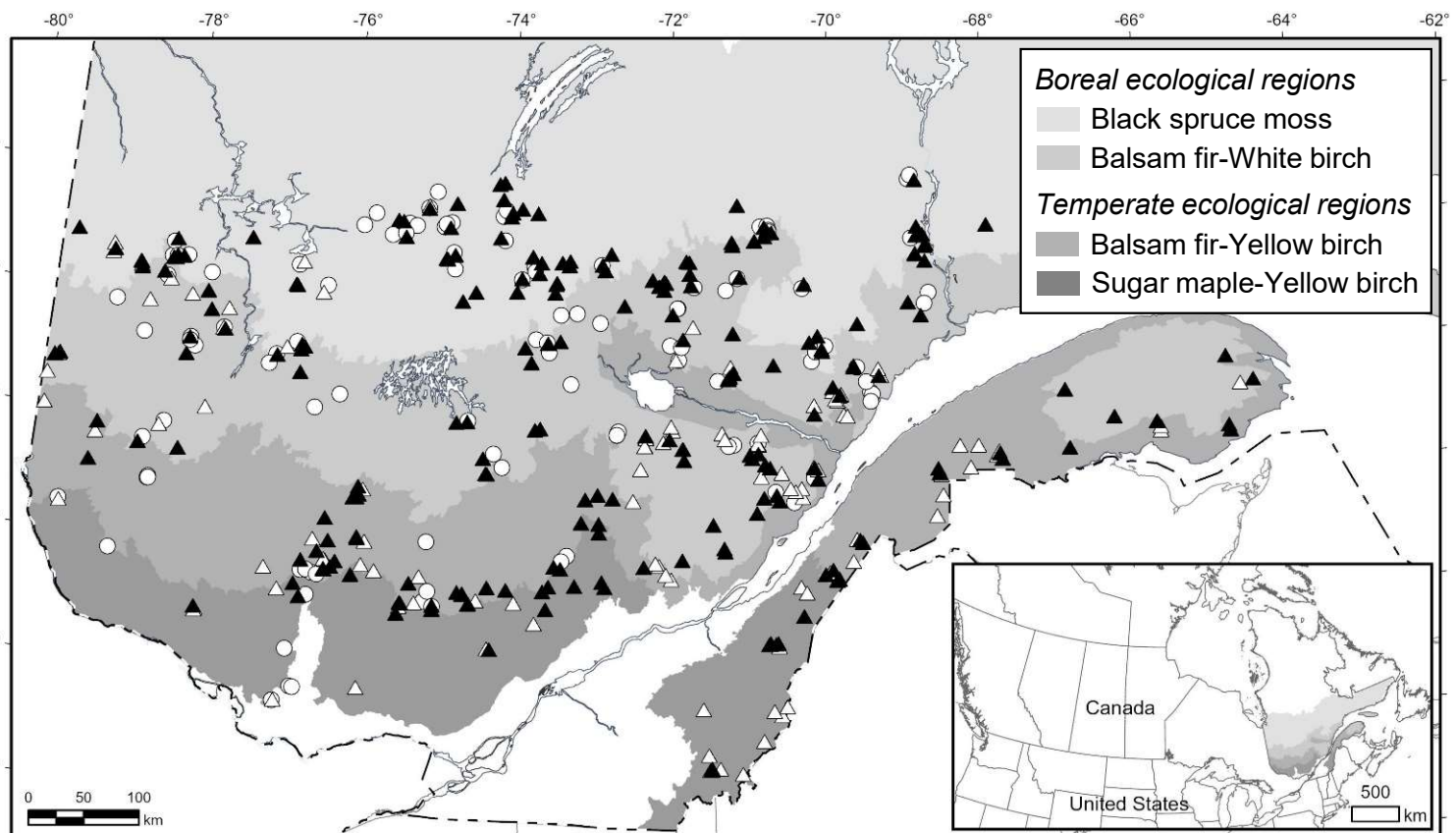
Fig 3 Yield gap according to site index in 26- to 34-year-old plantations.

Fig 4 Yield gap according to planting density in 26- to 34-year-old plantations.

Fig 5 Yield gap according to competition in 26- to 34-year-old plantations. X-axis runs from 100 to 0%. Competition was quantified as a percentage of the total stand basal area, calculated as: (basal area of naturally regenerated trees / (basal area of naturally regenerated trees + basal area of planted trees)) $\times 100$.

Fig 6 Composition of the competition in unsuccessful 26- to 34-year-old plantations with a plantation scenario that deviates from resilience-driven successional trajectories, i.e., black spruce and jack pine plantations that are located on balsam fir potential natural vegetations types and white spruce plantations that are located on balsam fir or on black spruce potential natural vegetation types.

Fig 7 Composition of the competition in unsuccessful 26- to 34-year-old plantations with a plantation scenario aligned with resilience-driven ,successional trajectories, i.e., black spruce and jack pine plantations that are located on black spruce potential natural vegetation types.

Fig 1 Martin Barrette et al.**Fig 1** Locations of plots in plantations of black spruce (black triangles; $n = 228$), white spruce (white triangles; $n = 131$) and jack pine (white circles; $n = 116$).

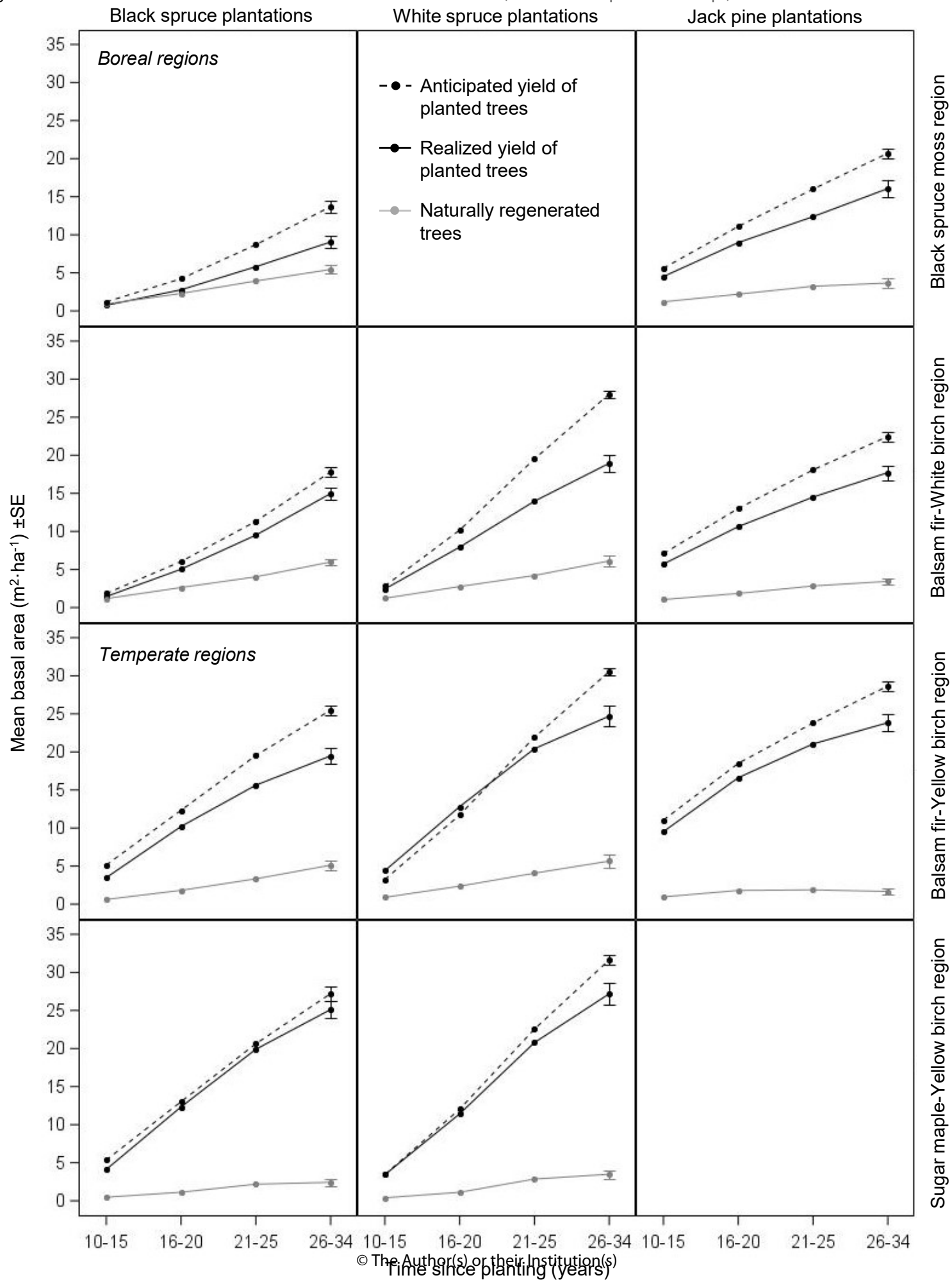


Fig 2 Realized vs anticipated plantation yield.

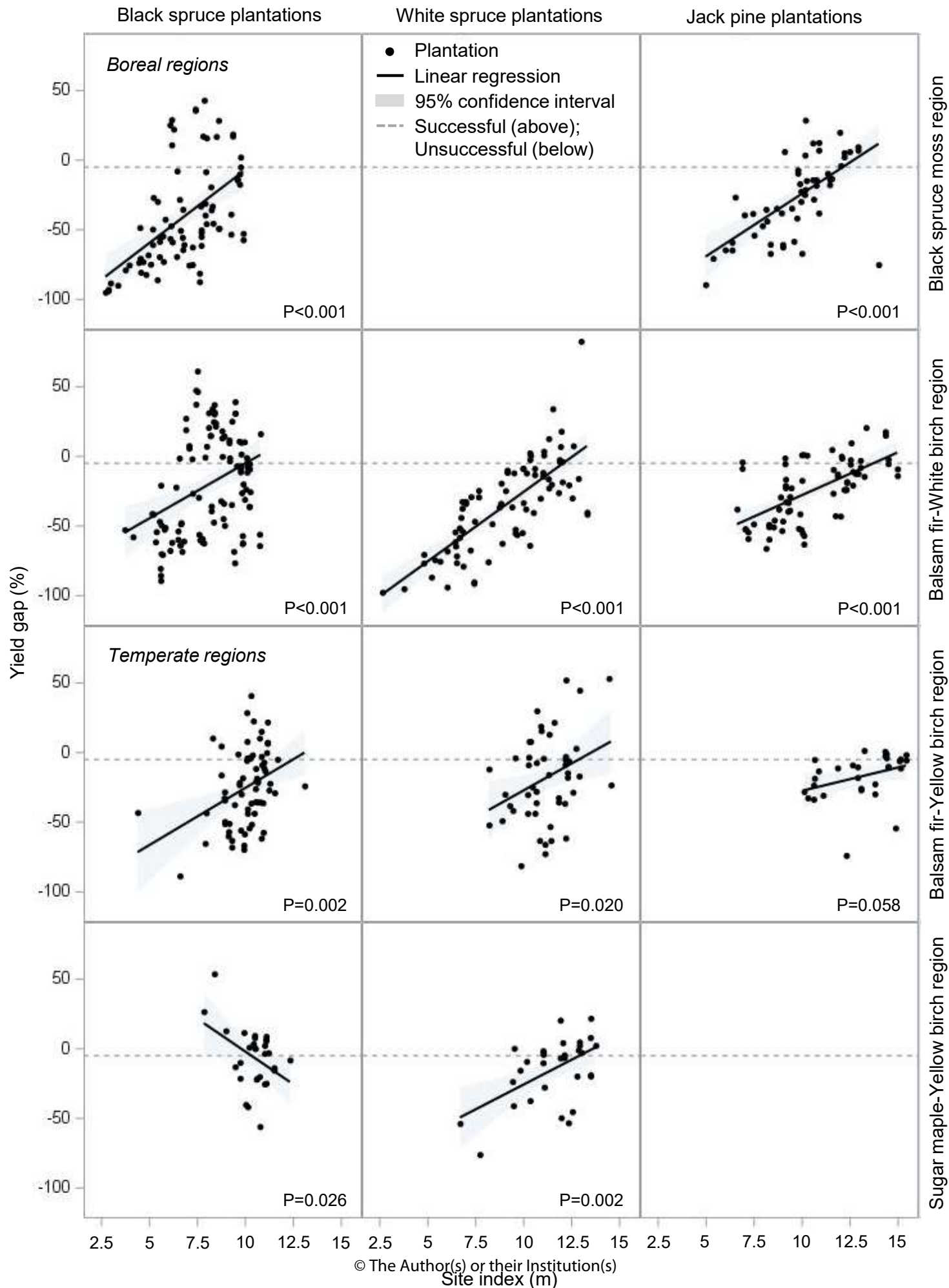
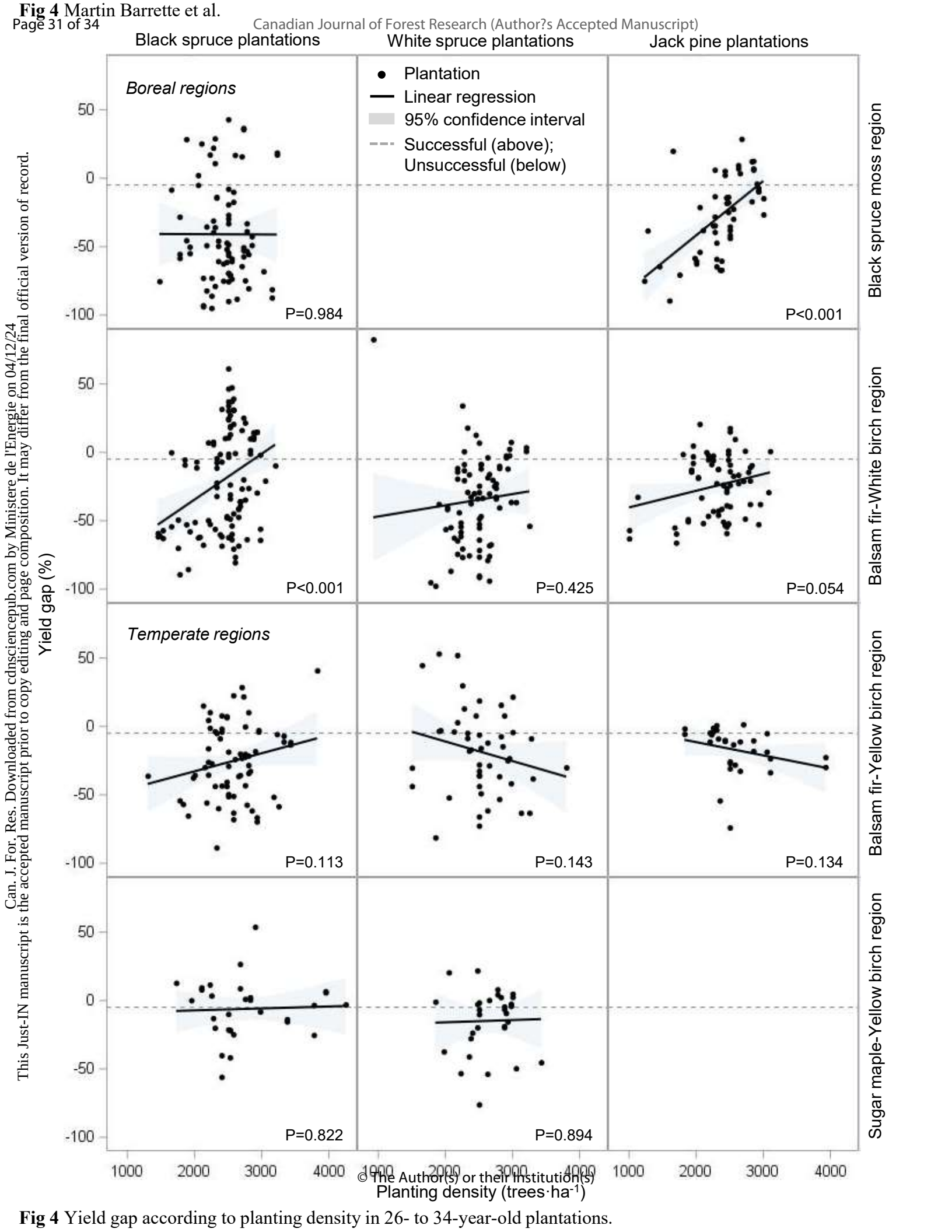
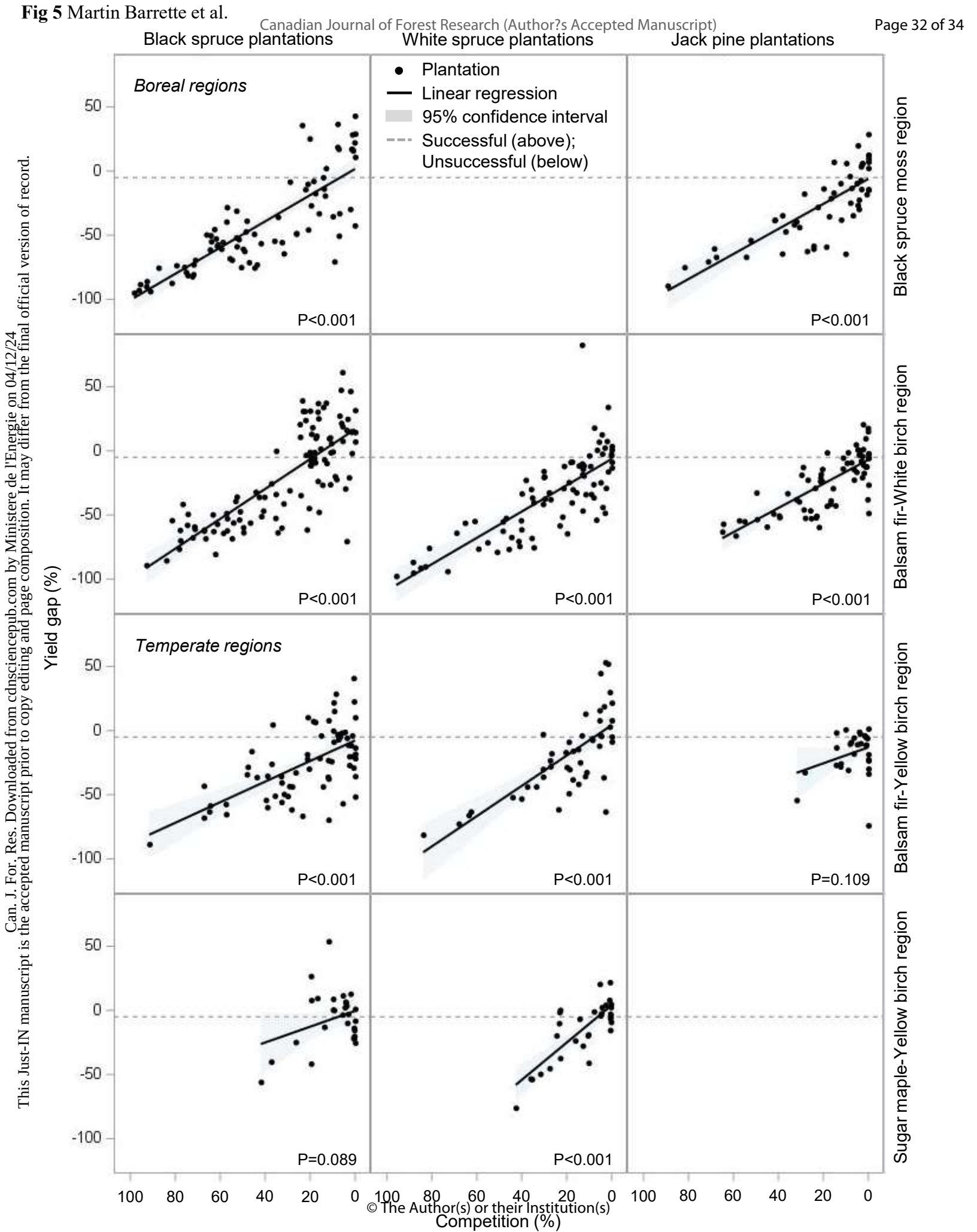


Fig 3 Yield gap according to site index in 26- to 34-year-old plantations.





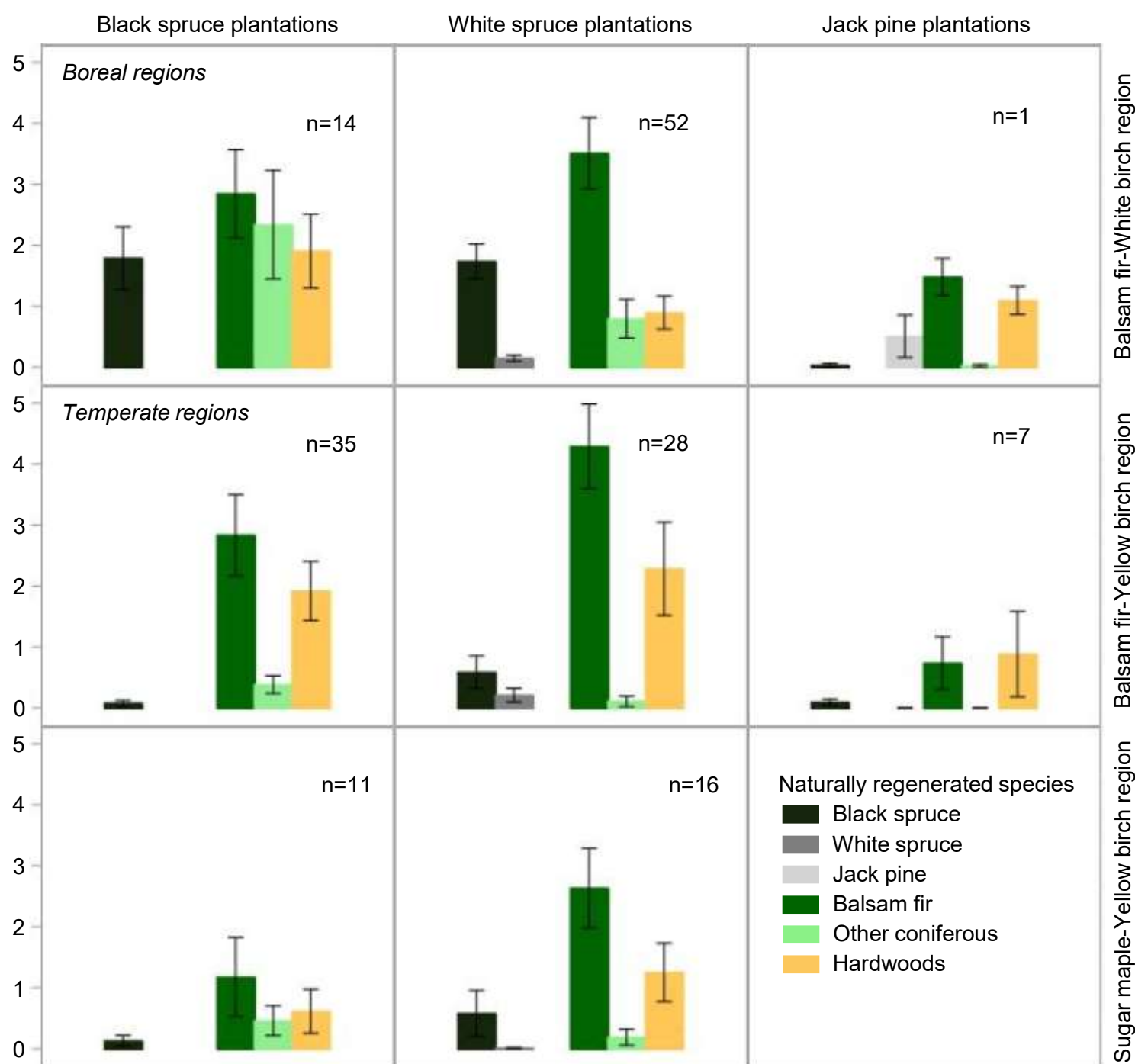


Fig 6 Composition of the competition in unsuccessful 26- to 34-year-old plantations with a plantation scenario that deviates from resilience-driven successional trajectories, i.e., black spruce and jack pine plantations that are located on balsam fir potential natural vegetation types and white spruce plantations that are located on balsam fir or on black spruce potential natural vegetation types.

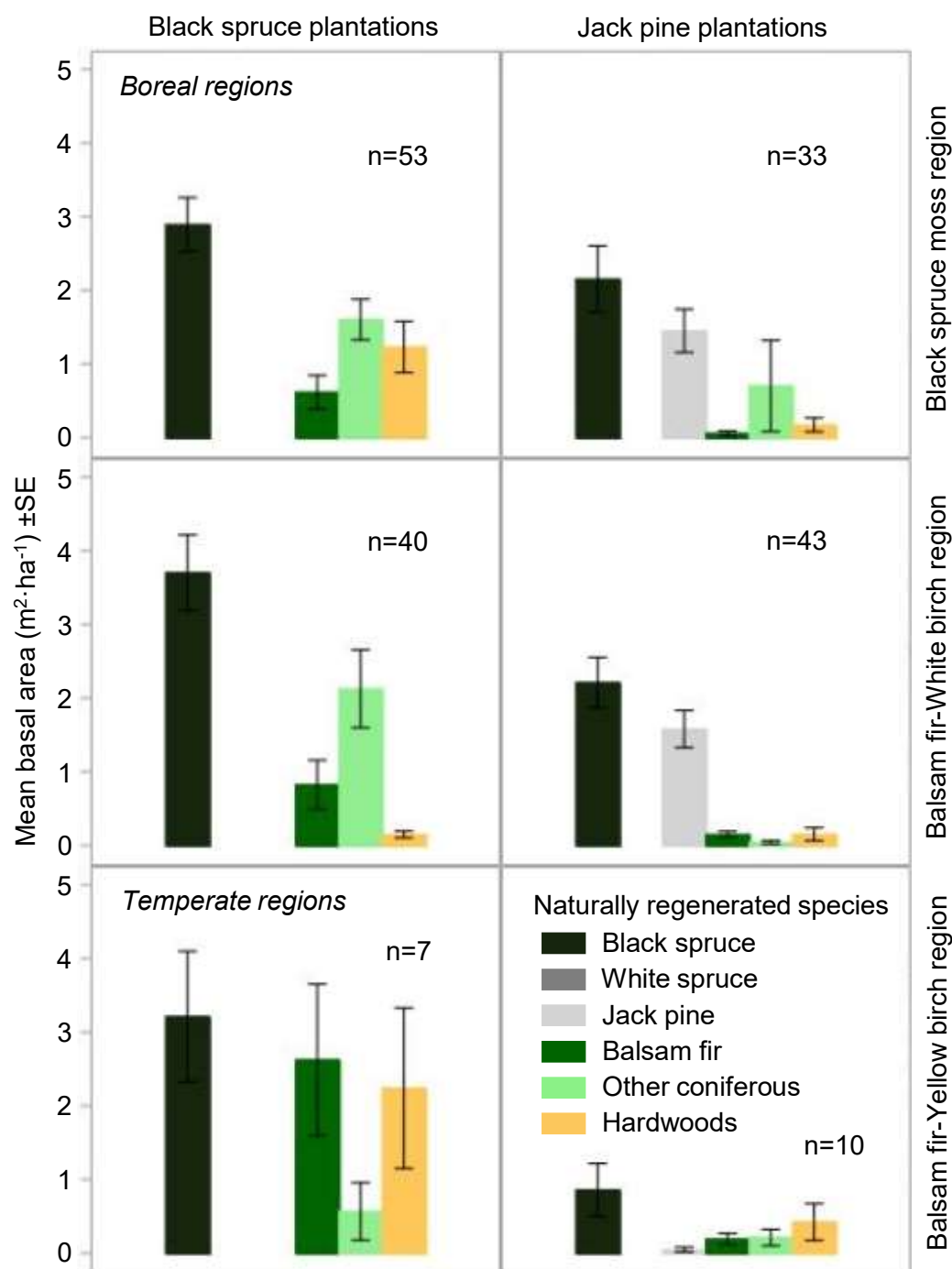


Fig 7 Composition of the competition in unsuccessful 26- to 34-year-old plantations with a plantation scenario aligned with resilience-driven ,successional trajectories, i.e., black spruce and jack pine plantations that are located on black spruce potential natural vegetation types.